DEC 23 1946

ARR No. 3F22

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

June 1943 as
Advance Restricted Report 3F22

RECOMMENDED TEST PROCEDURE FOR AIRCRAFT ENGINE TURBOSUPERCHARGER POWER PLANTS

By NACA Subcommittee on Recovery of Power from Exhaust Gas

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WASHINGTON

E-135

PREFACE

Due to the rapid development of turbosupercharged engine installations, considerable confusion has arisen regarding the proper method of testing and of interpreting the test results. A standardized test code is certainly undesirable at this time, but a record of the accumulated experiences of various engineers expressed in the form of a "Recommended Procedure" may be helpful. It may assist in avoiding certain pitfalls and serve as a point of departure for improved techniques and equipment. In the spirit of providing such a record, and with no thought to limit or oppose the test procedures now in use in various engineering organizations, this report is presented.

Members of the Subcommittee on Recovery of Power from Exhaust Gas whose recommendations are embodied in this report are:

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While many men and organizations have contributed generously in the preparation of this study, the Subcommittee on the Recovery of Power from Exhaust Gas wishes to acknowledge its particular indebtedness to the four men who prepared the final draft of this report. Messrs. W. O. Meckley and N. F. Frischhertz of the General Electric Company, G. E. Holbrook of the Turbo Engineering Corporation, and W. J. Colson of the Wright Aeronautical Corporation.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

RECOMMENDED TEST PROCEDURE FOR AIRCRAFT ENGINE TURBOSUPERCHARGER POWER PLANTS

By NACA Subcommittee on Recovery of Power from Exhaust Gas

I. INTRODUCTION

This procedure is designed to provide for the aircraft, engine, turbosupercharger manufacturers, and other interested groups a guide for instrumenting, testing, and presenting the over-all characteristics of any engine-turbosupercharger installation.

Primarily, a turbosupercharger and an engine are mechanisms for maintaining and utilizing a weight flow of air. The power delivered by the engine depends directly on the weight of combustible charge consumed per unit time; and the usefulness of the turbosupercharger is measured by its ability to provide the necessary air weight flow. Thus, the only bond between the two components of the system is air flow; and air flow is the only satisfactory means for relating, testing, and describing the performance of a turbosupercharger-engine combination. The particular significance of this fact, with regard to flight test planning, is clear. Adequate means for determining the air flow through the compressor, the engine, and the turbosupercharger must be made available. This may be done by calibrating the engine, the carburetor, or providing venturi meters or survey rakes in the intake ducts. The best method is to employ meters; however, particular installations may preclude their use. Air-flow determination must be deliberately and carefully provided for.

Experience has shown that too often the wrong kind of data is taken because of lack of preflight planning, appreciation of the problems involved, goals to be attained, and inadequate instrumentation. In general, it will require less than half as many conditions or points to establish a curve where specific variables are controlled as are required when only random observations are made. Thus, actually, considerable time and expense may be saved in the long run if well-controlled test conditions are maintained.

By closely adhering to the test procedure the above pitfalls may be eliminated and the maximum amount of useful and essential information will be obtained at a minimum of flight time and expense.

II. PURPOSE

The purpose of this procedure is to point out general methods of conducting and analyzing tests accurately and quickly to determine the safety and performance characteristics of an engine-turbosupercharger installation. In specific cases it may be desirable to conduct considerably more tests than specified. The scope of this report will extend only to that necessary to prove out a new installation and to provide data for a check of the performance analysis of the installation.

III. PREFLIGHT ANALYSIS OF ENGINE-TURBOSUPERCHARGER SYSTEM

Perhaps the greatest value of the preflight analysis is its educating influence on the interested personnel. The flight test crew members are thereby forwarned of otherwise confusing phenomena and are consequently able to get good reliable data without wasting flight time. The preliminary analysis will indicate what data should be taken to draw curves for answering any specific question or to solve a given problem. The possibility of recording a great amount of useless data is eliminated. If the data are taken as planned, the work of final analysis will be simplified. The rapidity with which postflight analysis can be made, if the pattern for analysis is already defined, makes it possible to formulate intelligent opinions and decisions before the next flight. Too often several flights of a program are finished before the results of the first are analyzed.

A. Construction of the Combined Performance Curves

In order to show the performance of the engine and the turbosupercharger on one curve sheet, coordinates must be selected which are common to both. The coordinates used here are air flow and carburetor air inlet pressure. Except for duct leakage, the weight flow of air through the compressor is the same as that through the engine. Also, the air flow, the fuel flow, and the waste-gate effective area, determine the flow through the turbine, again neglecting leakage. The carburetor inlet pressure is the compressor discharge pressure minus the duct loss and intercooler pressure drop. Thus the engine and turbosupercharger variables both may be plotted on the same coordinates of air flow and carburetor pressure.

In the case of an engine without turbosupercharging, carburetor pressure varies directly with altitude; the turbosupercharger, however, imposes a variable relation between carburetor pressure and altitude. As it would involve a three-dimensional plot to include altitude as a variable, it is held constant when constructing combined engine-turbosupercharger performance curves. An example of such a curve sheet is shown on figure 10 for a constant altitude. Normally these curve sheets are made at increments of 5000 feet altitude. In constructing these curves, the performance data for the engine, the turbosupercharger compressor, the intercooler, and the turbine are calculated separately and superimposed on the single set of coordinates.

1. Engine Performance

Adequate information must be obtained from the engine manufacturer on the air-flow characteristics of the engine. The necessary engine curves are: An air-flow calibration (air flow vs. carburetor air pressure at various engine speeds with corrections for (a) carburetor air temperature, (b) exhaust back pressure, (c) effect of carburetor air temperature (C.A.T.) on manifold absolute pressure (M.A.P.) lines); power calibration of engine at best power with corrections for variation in mixture strength, and specific fuel consumption against engine revolutions per minute for constant horsepower lines. Examples of the forms used are shown in figures 1, 2, and 3.

In using these data, they are first replotted in the form shown in figure 4. The following should be noted concerning this engine-performance plot:

a. The data are for the same carburetor mixture as the original data - generally best power mixture.

b. The engine curves are full throttle or for one definite part-throttle position.

c. The exhaust back pressure is assumed equal to the carburetor pressure.

d. A fixed carburetor air temperature is assumed, usually 100° F. The change from one carburetor air temperature to another is usually accomplished by means of the relation

$$\frac{\text{Air flow}_1}{\text{Air flow}_2} = \frac{T_2 \text{ absolute}}{T_1 \text{ absolute}}$$

2. Performance of Turbosupercharger Compressor

Specification curves for the turbosupercharger compressor will be supplied by the turbosupercharger manufacturer. Figure 5 illustrates one type of compressor performance curve. This chart is used to find compressor speed and discharge temperature for given operating conditions. The method is indicated by the example traced out on the chart. Due to the variation of efficiency with the Mach number, it is necessary to correct the speed obtained from the chart for inlet temperature. A correction curve is provided.

It will be noticed that the chart has been plotted using values of inlet temperature and pressure rather than altitude. This has been done so that inlet conditions other than those of the NACA altitude may be easily handled. Such conditions arise from the consideration of inlet ram and pressure drop in the inlet duct, from use of standard summer air and temperature rise in the inlet duct.

3. Intercooler Performance

The data desired for a complete analysis are:

a. The pressure drop of the engine air as a function of the weight flow of engine air and the density at the intercooler entrance and exit

b. The intercooler effectiveness, which is defined as

$$I.E. = \frac{T_e - T_d}{T_e - T_c}$$

where

T_e temperature of engine air at intercooler entrance

T_d temperature of engine air at intercooler discharge

T_c temperature of cooling air at cooling air entrance

The effectiveness depends on both the engine air flow and the cooling air flow; the cooling air flow in turn is dependent upon the dynamic pressure of flight, the flight altitude, and the intercooler ducting. The intercooler performance therefore becomes involved in the aerodynamics of the airplane. Since this is the case, it is usual to assume a pressure drop and a carburetor air temperature, 1 inch of mercury and 100° F, respectively, being representative of good installations.

4. Turbine Performance

The function of the supercharger turbine is to furnish the power required by the compressor. It affects the over-all power plant chiefly by the back pressure it imposes on the engine, and the limitation on the range of operation determined by the closing of the waste gate. Thus, the items of interest are the nozzle-box pressure and temperature and the power condition at which closed waste gate occurs.

The turbine performance data are supplied by the turbosupercharger manufacturer. Figure 6 illustrates one type of turbine performance curve. The method of determining the nozzle-box pressure for a given condition is indicated by the example traced out on the chart,

The two altitude scales on the turbine chart are scales for the back pressure on the turbine. If, because of an exhaust hood or the pressure distribution about the airplane, this turbine discharge pressure differs from the atmospheric pressure, the altitude equivalent of the actual pressure would be used.

The waste-gate position depends upon the difference between engine exhaust weight flow and turbine weight flow, and leakage in the exhaust ducting.

It is usually desirable, in calculating waste-gate position, to neglect leakage flow, and then to correct the waste-gate position obtained for an assumed leakage. Exhaust leakage varies among similar installations and even from day to day on the same installation. Due to the uncertainty of this factor, it is convenient not to introduce it into the calculations, but to take it into account at the end in the form of a correction factor.

To calculate the waste-gate position:

1. Determine the total exhaust flow by adding the engine air flow and the fuel flow, as obtained from the engine curves.

2. Calculate the flow through the turbine nozzles. A curve such as that shown in figure 7, together with the turbine nozzle effective area, can be obtained from the turbosupercharger manufacturer.

3. Subtracting the turbine nozzle flow from the total exhaust flow gives the waste-gate flow plus leakage flow.

4. Assume leakage flow equals zero.

5. Using figure 7 and the same nozzle-box pressure used in step (2), the waste-gate effective area is obtained.

6. A curve such as that shown in figure 8 may be obtained from the turbosupercharger manufacturer. This will give the waste-gate angle corresponding to this effective area.

7. A correction for leakage is now applied if desired. The effective leakage area is estimated as a percentage of the sum of the effective nozzle area and waste-gate area (found in step (5)). The effective leakage area is subtracted from the waste gate area and the angle corresponding to this net waste-gate area is obtained from figure 8.

5. Combined Performance

To construct the combined performance curves, lines of constant compressor speed, compressor discharge temperature, nozzle-box pressure, pulsation, and waste-gate position are superimposed on the engine curves as shown in figure 10.

a. Compressor speed lines

By means of the compressor specification chart (fig. 5), several points on a line of constant compressor speed can be found in terms of air flow and compressor discharge pressure for a given altitude. Assuming a constant representative intercooler pressure drop, these points can be plotted directly on the basic air flow - carburetor air pressure coordinates.

b. Compressor discharge temperature

Lines of constant discharge temperature are obtained in a similar manner.

c. Nozzle-box pressure lines

From the turbine specification sheet (fig. 6), the nozzle-box pressure is found for several compressor weight flows at a given compressor temperature rise and altitude. These values, as well as those for several other temperature rises, are plotted against air flow for constant values of compressor temperature rise. From this plot, points of compressor temperature rise against air flow for a constant nozzle-box pressure can be read off. The temperature rise is then converted to compressor discharge temperature and the lines of constant nozzle-box pressure plotted on the combined performance sheet using air flow and compressor discharge temperature as coordinates.

d. Waste-gate position lines

The waste-gate position must be calculated, as explained in section 4 above, and lines of constant waste-gate angle plotted on the sheet.

B. Use of the Combined Performance Curves for Preflight Analysis

1. Altitude Curves

It has been explained that the combined performance curves can be plotted only at constant altitude. It is essential in flight test work to predict the changes that take place in the variables with altitude. To plot variable altitude curves, it is only necessary to cross-plot the various engine-turbosupercharger variables which are shown on figure 10.

These curves can be used for predicting the data that will be recorded during a rated power climb, for instance, and will warn of any limiting condition that might be approached during the climb or during the level runs at any altitude. They can also be used for predicting critical altitudes due to limiting turbosupercharger speed, closed waste gate, or compressor pulsation. A method for estimating critical altitudes from the compressor specification curves is given in section C, below.

2. Range of Power, Closed Waste Gate, and Pulsation Limit Runs at Constant Altitude

The combined performance charts suggest several methods of obtaining the desired results. Each method has its advantages depending upon the use for which the data are intended and the speed and ease at which they can be obtained.

a. Constant engine revolutions per minute

This method of testing will provide data which may be easily correlated with the pre-flight analysis and will provide information for flight operational instructions. In this method, the manifold absolute pressure is varied by means of turbo boost along a constant engine speed line. Approximately equally distributed test points should be obtained at each of the designated engine-revolutions-per-minute values over a range of manifold pressures. The following engine revolutions per minute should be tested: military, normal, and then further reduced in small decrements (usually 200 rpm). The initial manifold pressure at each engine revolutions per minute should be the highest permitted by the engine manufacturer for that revolution per minute, and the lowest may be that at zero turbosupercharger boost. The manifold pressure should then be reduced in decrements of approximately 4 inches of mercury or in such decrements that four test points will cover the normal expected manifold pressure range. When the range of manifold pressures to be tested is limited by closed waste gate, compressor pulsation, or system instabilities, it is then preferable that the initial manifold pressure be the minimum and increased in increments until the limiting factor is reached.

b. Decreasing engine speed at constant brake mean effective pressure

In this method, the closed waste-gate line will be intersected at nearly a right angle.

The procedure is slightly more difficult to perform since an automatic control is not available for holding brake mean effective pressure constant and two controls must be adjusted to obtain the desired condition.

c. Constant turbosupercharger speed

Varying engine speed and turbosupercharger boost so as to hold the turbosupercharger speed constant also results in a good intersection of the closed waste-gate line. The method of control is the same as in "b".

d. Closed waste-gate line

The easiest method of obtaining data at closed waste gate is by operating along the closed waste-gate line itself. The method of getting onto the closed waste-gate line is to reduce the engine speed to a low value and then apply full turbo control. With this condition, the regulator is calling for more pressure than is available and closes the waste gate. Points along the line may be obtained by increasing the engine speed in small increments until limiting conditions are reached.

e. Pulsation limit

Under some conditions on some installations, compressor pulsation will be encountered before closed waste gate is reached. The compressor pulsation line is therefore a limiting condition and is determined by the procedures as described above.

Note: The above tests should be conducted at full throttle; however, if part-throttle operation is desired, the above procedures may be repeated at the desired constant throttle setting. Additional charts similar to figure 10 will be required to show part-throttle performance.

C. Method of Estimating Critical Altitude on the Compressor Specification Chart (Fig. 5)

1. Choose the engine power for which the critical altitude is desired.

2. Obtain the corresponding weight flow from the engine curves.

3. Choose an altitude near the expected critical altitude.

4. Enter compressor specification chart at lower left weight flow scale, proceed vertically upward to the altitude temperature, horizontally to the altitude compressor inlet pressure, and vertically to upper right quadrant.

5. Obtain required carburetor pressure from engine curves.

6. Add estimated intercooler and duct loss (usually assumed as 1 in. Hg). This gives the required compressor discharge pressure.

7. Enter chart at the required compressor discharge pressure, proceed vertically upward to the altitude compressor inlet pressure, and horizontally to intersect the line drawn in step (4) in the upper right quadrant. This gives the first point of a line of constant mass air flow which is equivalent to constant engine power.

8. Repeat steps (4) and (7) for several altitudes until well above the expected critical altitude and connect the points to give the constant mass air-flow line.

9. Divide the rated compressor speed by the correction factor for the temperature corresponding to the expected critical altitude.

10. Sketch the corrected speed on figure 5 and read the critical altitude at the intersection of the constant mass air flow line with the limiting turbosupercharger speed line.

11. If further refinement is desired, divide rated speed by the correction factor for the temperature corresponding to the critical altitude found in step (10) sketch in the new corrected speed line, and read final estimated critical altitude from intersection with air mass flow line. If the first estimation was reasonably close, this last step will be unnecessary.

12. Note that ram at the compressor inlet and inlet temperatures differing from standard altitude temperatures may be taken into account in the process if desired.

13. Critical altitude caused by compressor pulsation will be evident if the plotted constant air mass flow line crosses the pulsation line on the chart.

D. Method of Estimating Critical Altitude from the Combined Performance Chart (Fig. 10)

1. Straight-line interpolation between the charts is sufficiently accurate for estimating critical altitude.

IV. REQUIRED ENGINE-TURBOSUPERCHARGER TESTS

The problem of reducing the human factor is as important in flight test procedures as it is on data recording (as described in sec. V). Procedures must be developed and thoroughly indoctrinated in the flight personnel to prevent errors in decisions and observations made during the flight. The flight crew must understand the specific problems of each test and understand what the data are expected to demonstrate or prove. Developing such an understanding of the test will prevent irrational test in flight and will qualify the flight engineer to make unscheduled checks in flight necessary to explore any peculiar condition. The greater the effort toward educating flight personnel the better and more economical will the test become.

In general, some important variable should be held constant while other variables are varied to obtain the desired curve. Before flight it should be decided what is to be proved or learned by the test. The analysis engineer should establish the curves necessary to prove the given problem. The flight engineer is required to take data from which these curves may be drawn.

The following will describe tests necessary to establish the over-all engine-turbosupercharger performance from the standpoint of proving out the installation with respect to safety, cooling and mechanical operation, as well as engine-turbosupercharger performance. Additional tests may be necessary to answer specific questions and to provide complete design performance data but are not included in this report.

Engine-turbosupercharger combination tests should be divided into two general classifications:

A. Installation Tests

B. Performance Tests

The following tests should be run for both the above classifications:

Ground test on engine nacelle test stand (if available)

Ground run with installation in the completed airplane

Flight tests

The background for the high-altitude flight tests will be the ground and low-altitude tests. This should sufficiently prove the installation so that high-altitude tests can be free from as many uncertainties in the installation as is possible.

A. Installation Tests

1. Engine Nacelle Test Stand

a. Functional operation of installation

b. Functional performance of component parts

(1) General operation of engine (carburetion, cooling, and accessories)

(2) Ducting - leakage in exhaust and induction systems

(3) General operation of turbosupercharger system (lubrication mechanical operation of turbosupercharger, wheel temperature, exhaust flaming, etc.)

c. Special tests

(1) To be decided by agreement between interested parties

d. Data to be obtained

(1) Record all data of section VI A and B

e. Test procedure

(1) Run various speeds and powers as recommended by engine and turbosupercharger manufacturers.

2. Engine turbosupercharger installation in completed airplane. Tests to be conducted should be similar to those of the ground test stand.

3. Flight Tests

These should include tests similar to the ground tests and should include aerodynamic and altitude effects on the installation. Check functioning of all instrumentation and test equipment. Action of power-plant controls, and their characteristics should be noted.

B. Performance Tests

1. Engine Nacelle Test Stand

a. Requirements for take-off

b. Special tests

(1) To be decided by agreement between interested parties.

c. Data to be obtained

(1) Record all data of VI B and if desired VI A. Basic engine data are necessary; the other data will provide an opportunity to work out instrumentation problems and technique.

d. Test procedure

(1) Run various powers to cover as wide a range as possible of exhaust back pressures, carburetor air pressures, and so forth.

2. Engine-turbosupercharger installation in completed airplane. Tests to be conducted should be similar to those of the ground test stand.

3. Flight Tests

a. Low altitude flight (below 15,000 ft)

(1) Take-offs for the first flights of a turbo installation should be made with the turbo control in the low boost position. Use turbo for take-off only after the safe functional operation of the power plant has been proved in flight. At altitudes below 15,000 feet set rated and military power at full throttle, turbo as required, mixture as specified. Take photos of instruments. In this flight, check functioning of all instrumentation and test equipment. Action of power plant controls and their characteristics should be noted.

(2) Flight tests should be made to conform to the data as described in III B of Preflight Analysis. Pulsation is not likely to be encountered during these low-altitude flights.

(3) Data to be obtained

(a) Record all data of section VI B and if desired VI A.

(4) Procedures

(a) Same as described in this section under high-altitude flight

b. High altitude flight (above 15,000 ft)

(1) Performance tests desired

(a) Critical altitudes

(b) Closed waste-gate lines

(c) Pulsation lines

(d) Power accelerating characteristics

(e) Power-control characteristics

(f) Special tests

(2) Methods of obtaining desired results

The object of tests (1) (a), (b), and (c) above should be to provide checks on the preflight analysis discussed in section III. The data required will be determined by running constant engine-revolutions-per-minute lines in level flight at various altitudes, usually in 5000 feet levels. From these data the items of (1) (a), (b), and (c) above may be determined.

(a) Data to be recorded: All readings indicated in VI B and if desired VI A.

(b) Test procedure:

At full throttle, mixture as specified for the engine revolutions per minute, intercooler shutter open, the following procedure should be followed:

Set engine revolutions per minute.

Adjust turbosupercharger boost until limiting manifold pressure or turbosupercharger speed is reached. Allow a short period of time for stabilization. Record data and decrease manifold pressure approximately 4 inches of mercury. Repeat until the desired manifold pressure range is covered. The above procedure should be repeated at the designated engine revolutions per minute until closed waste gate, compressor pulsation, or system instability becomes a limiting factor. At these points it has been found advisable to start at the minimum manifold pressure and increase until the limiting condition is reached.

If found necessary, the above procedure may be repeated for part throttle operation and/or for checking effect of intercooler.

By proper coordination of the test the above procedure may be quickly accomplished. Such data, including stabilization, have been obtained at a rate of less than 2 minutes per condition. Certain data may be obtained by methods other than "area" (i.e., constant engine rpm) testing. Thus for data at specific operating limitations the procedure is as follows:

Critical Altitude (max. limiting turbosupercharger speed)

From the level flight data critical altitudes may be accurately estimated by interpolation for all powers. When data at critical altitude are required, short constant power, constant revolution per minute climbs may be made so that data will bracket estimated critical altitude.

For example, a military power critical altitude climb would proceed as follows:

From level flight data or preliminary analysis estimate the military power critical altitude. At an altitude of approximately 5000 feet below estimate set military power on test engine at full throttle, mixture as specified, and so forth, and begin climb.

Take readings every 500 feet altitude. When the maximum turbine speed is reached, take reading and regulate turbosupercharger revolutions per minute to this constant value. Continue to climb and reduce power to rated conditions at end of 5-minute limit.

Limiting Powers as Determined by Closed-Waste-Gate Lines

The following procedure should be used to establish a closed waste-gate line. Closed waste-gate conditions are the only turbo conditions that are sensitive to changes in ram. Ram, therefore, should be held constant or allowed to vary according to normal change in speed with change in power.

Hold the airspeed constant on multiengine airplanes. Hold airplane altitude constant, open throttle full, mixture as specified, intercooler shutters full open.

Reduce turbo boost to low position. Reduce engine revolutions per minute to a low value (e.g., 1400). Specific values are used for illustrative purposes only. Advance turbosupercharger boost to the high position. (The first motion of the boost control causes a slight increase in engine power and the regulator closes the waste gate. Any further motion of the boost control has no effect whatsoever on the power condition. From now on through this curve the regulator is inoperative.) Take a reading at 1400 rpm. Advance propeller governor control to give 1500 rpm (at closed waste gate the excess exhaust gas available to accelerate the turbosupercharger is practically nil; trpm will increase slowly). When turbosupercharger revolutions per minute have increased and stabilized, take reading.

Increase engine revolutions per minute to 1600. Allow turbosupercharger revolutions per minute to stabilize and take reading.

Increase engine revolutions per minute to 1700 (or enough to cause rise in carburetor air pressure of approx. 4 in. Hg). Take reading. Repeat process until condition is limited by excessive manifold absolute pressure or compressor plusation system instability is reached. As soon as the run is complete retard turbosupercharger boost control so that excessive manifold absolute pressure will not be developed in the event that the engine revolutions per minute should be increased further.

(3) Technique for determining accelerating characteristics

Record time in seconds to move control to new position and additional seconds for system to reach new condition. Take all readings indicated in VI B.

Adjust turbosupercharger control to give desired power (e.g., normal or military) with throttle wide open. Close throttle, leaving turbosupercharger control set. Do not exceed critical turbosupercharger revolutions per minute and keep well out of pulsation. Open throttle as fast as practicable. A similar procedure should be employed to determine the time to govern from low to high powers and high to low. Tests should be repeated at several altitudes, immediately upon attaining the desired altitude and after 15 minutes at altitude.

An alternate test would be to determine the time required to change from cruising engine power condition to normal or military condition with varying engine speed.

Adjust power plant controls to give normal cruising power with full throttle and record time in seconds to move controls to new position and additional seconds for system to reach new condition. Take all readings indicated in VI B.

Repeat the above procedure for several different sequences or techniques of power plant control operation.

Tests should be repeated at several altitudes, immediately upon attaining the desired altitude and after 15 minutes at altitude.

(4) Procedure for investigating control characteristics

Due to the considerable number of regulator types now available, it is not practical to give all test procedures in this report. In general, the procedure should consist of determining the validity of the manufacturer's specifications by climbing at constant regulator control settings. Also the stability characteristics during steady and transient conditions should be observed during tests by continuous photo recording. External influences such as control cables, rods, cockpit controls, and so forth, should be evaluated in appraising the characteristics of regulator.

Take all readings indicated in VI B.

V. FUNDAMENTAL OF ACCURATE DATA RECORDING

A. Personnel Instruction

The personnel in charge of specific observing stations should be qualified by previous test engineering and demonstrated reliability on previous flight tests. Unless indoctrinated by immediately preceding flights, they should be given detail instruction on their duties and their share of the flight program and its importance to the final results.

B. Mechanical Recording of Data

The recording of performance data must be free of human errors, and accomplished by synchronized mechanical means. This necessitates full photo and/or chart recording of data. In all cases automatic temperature recording should be used if available.

Even under the ideal conditions of comfort and space found on a test stand, manual data recording cannot hope to compete with the accuracy and speed of a photo recorder. In an airplane, working conditions are much worse and manually recorded data become bad at best. Accurate analysis is almost impossible with manually recorded data. Photo recording leaves the flight engineers free to handle their job - that of observing (instead of hurrying to get manual readings while something important is being missed). Photo recording does not eliminate the flight engineer. It makes his position more valuable in that it leaves him free to apply engineering supervision instead of push a pencil.

No manual data should be taken except that which is required to provide a log of the flight. It definitely compromises the decisions made regarding the flight and often reflects personalities rather than facts.

C. Synchronization of Readings

If more than one photo panel is used, all cameras must by synchronized to take a picture at the same instant of time so that all data will be properly correlated. This one item - correlation of all data with respect to time will improve the consistency of data more than any other precaution.

During a recent series of tests an automatic continuous strip recorder was used to record engine data. A simulated brake mean effective pressure, revolutions per minute curve (similar to many actually observed) will be drawn for illustrative purposes. The foregoing record (fig. 9) was made for a supposedly constant, stable power condition. Notice that three variations or oscillations exist. The minute fluctuations due to instrument vibration are usually inconsequential and can be averaged out by reasonably long exposures. The cycle observed between A and B takes place over irregular intervals and is easily distinguishable. The cycle between 1 and 2 is likewise readily observed and is at specified test condition.

Now suppose that one observer is recording revolutions per minute each minute; another is recording brake mean effective pressure, at a different station, each minute. If the revolutions per minute recorder makes an observation at C and a few seconds later the brake mean effective pressure recorder takes his observation at D, the product or brake horsepower will be considerably in error for either instant.

(Even on a test stand where all conditions can be accurately controlled, these variations can be detected. In flight where conditions cannot be controlled, such variations are accentuated.)

In the past, flight tests were only functional checks, and since no analysis was intended such errors were tolerated. With the present trend toward scientific analysis of all flight problems, it is imperative that the data be equal to or of greater accuracy than that needed for the type of analysis planned.

A word must be said about temperature recording. Exact correlation with respect to time is not essential. Unlike manometers the temperature readings are not a function of the acceleration of the airplane or roughness of the air, nor are temperatures noticeably responsive to variations in power that occur over a period up to 5 or 10 seconds. (See A to B, fig. 9.) They are responsive to changes in power that occur over a period more than 15 seconds. (See 1 to 2, fig. 9.) It is obvious that correlation within a few seconds of time is sufficiently accurate for temperature recording. When an automatic recorder is used many temperatures may be taken and several complete cycles may b made during the running of a curve. The potentiometer operation should be adjusted to cycle the performance data during the interval of photo observation, and the general information readings may be spaced between such observations.

When an automatic recorder is used, the frequency of cycling should be fast enough so that the temperature may be taken off the chart at the time nearest the photo exposure without plotting the temperatures against time.

Any manometer station should be equipped with a sensitive vertical accelerometer. Any photo which shows an acceleration (vertical) greater than 0.02g should never be transcribed unless suitable corrections can be worked out and applied. The manometer observer should be second to the engineer conducting the test in experience and knowledge of the test and should operate the master switch for the cameras. The manometers are the most responsive indication of flight variables and must be correctly observed to assure that the data will be useful. It is useless to take data while large oscillations occur at the manometers - unless, of course, specific oscillations are being investigated and a motion picture camera is being used.

The extreme value of effective technique in recording data cannot be overestimated. Constant thought and training must be applied to this item.

VI. MEASUREMENTS TO RECORD

A. Installation Data (Preliminary)

The following measurements will provide information pertaining to the safety and mechanical design of the installation which must be checked at the start. These readings need not be observed simultaneously nor mechanically, but should conform to the accuracy requirement of the performance data, if necessary. The number and nature of readings to be observed should be specified and agreed upon by the engine, turbosupercharger, and airplane manufacturers.

1. Engine Data

    a. Engine cylinder head and base or coolant (in and out) temperatures

    b. Engine oil temperatures

    c. Engine oil pressures

    d. Intake manifold temperature and pressure

    e. Fuel-air ratio by thermal conductivity or fuel flow rate

    f. Exhaust back pressure at engine

    g. Baffle or radiator pressure drop

2. Turbo Data

    a. Oil system temperatures

    b. Oil system pressures and/or flow

    c. Temperature of the turbine parts; wheel, nozzle box, heat shields, exhaust manifolds; and so forth

    d. Temperature and flow data of the turbine cooling system

3. Duct Data, Leakage Tests, Pressure Loss, Velocity and Temperature Surveys

   a. Compressor inlet duct

   b. Compressor to carburetor duct

   c. Intercooler cooling air duct, in and out

4. Aircraft Data

   a. Metal temperature of housing, shields, shrouds, and so forth, around exhaust system

   b. Skin temperature of nacelle or structure immediately around, and aft of the exhaust discharge passage

B. Performance Data

The following measurements are the minimum required for performance analysis and must be measured accurately and simultaneously.

1. General Data

   a. Time - hours, minutes, and seconds

   b. Pressure altitude

   c. Atmospheric temperature, free air

   d. Indicated airspeed

   e. Engine revolutions per minute

   f. Brake mean effective pressure or engine torque

   g. Throttle position

   h. Mixture setting

   i. Waste gate position

   j. Turbo revolutions per minute

k. Carburetor air flow

l. Carburetor fuel flow

2. Pressures (all shielded total head except where noted)

   a. Compressor inlet, absolute or differential above air static

   b. Compressor outlet, absolute or differential above air static

   c. Carburetor inlet, absolute or differential above air static

   d. Nozzle-box inlet, absolute or differential above air static.

   e. Turbine exhaust tail-pipe pressure

   f. Manifold, absolute inches of mercury (static)

   g. Intercooler engine air drop, differential

   h. Intercooler cooling air drop, differential

3. Temperatures (deg F or C)

   a. Compressor inlet air

   b. Compressor outlet air or compressor air rise, differential

   c. Carburetor inlet air

   d. Exhaust gas nozzle box

   e. Intercooler engine air drop, differential

   f. Intercooler cooling air rise, differential

VII. INSTRUMENTATION (METHODS OF MEASUREMENTS)

It is patent that flight type of service instruments can form the backbone of the instrument setup, and they should be used where suitable. Due to mandatory mechanical recording, any manually balanced or adjusted instruments such as conventional potentiometers are ruled out. All instruments must be of the direct indicating or automatically recording type. Special non-service apparatus should be checked carefully before use for possible errors due to shift in position, acceleration in all directions, vibration, rapid change in ambient temperature and pressure, and so forth. The use of manometers is acceptable with certain limitations (see below) but the aneroid or airspeed type of pressure gage is much more convenient and requires no engineering attention during observations.

If an accurate difference is required, such as the pressure drop across an intercooler, or the temperature rise in the compressor, it should be measured as a difference directly rather than derived from the difference of the two absolute readings involved. This need not be an extra instrument as one of the absolute reading instruments, sometimes both, are eliminated.

A. Pressures

All pressure taps in the engine air and induction system should be shielded total-head type except those in the manifold. The shielded or venturi type consists of a small impact tube mounted with the open end at the throat of a small venturi and the whole unit mounted in the air stream. This type has the advantage of being comparatively insensitive to changes in angle between direction of flow and axis of impact tube.

The tube connections to the instruments on the photo panel should have a minimum inside diameter of 0.18 inch. Smaller holes than this are very susceptible to accumulation of slugs of liquid and are hypersensitive to minute leaks in the system. There are some remote indicating electric pressure gages at present available which may be used provided their reliability and temperature stability are assured.

In deciding upon the point of measurement, consideration should be given to the turbulence and stratification present, and to the pressure rise or drop between the point of measurement and the point at which the pressure is desired. Although the normal rules are generally not practicable in airplane installation, the following principles should be considered:

1. Measurements should be made as far downstream as possible from any bends or obstructions, preferably 10 pipe diameters.

2. Measurements should not be closer than 2 pipe diameters to a downstream bend or obstruction.

3. Measurements should not be located close behind temperature measuring elements or any other obstruction.

4. Impact pressures should be measured at a point of average velocity, normally at an immersion of 15 percent of the pipe diameter unless otherwise indicated by the duct surveys mentioned in VI A 3.

It is definitely recommended that pressures included in the performance data be measured by flight type of aneroid or differential pressure gages, such as the absolute manifold pressure gage and the indicated airspeed gage. The latter should be calibrated in inches of water or inches of mercury.

Altitude should be indicated by a sensitive altimeter or its equivalent connected to the static tube of the airspeed head.

If manometers are used, they should be of the single-leg reservoir type arranged in a closely spaced bank and have both end manometers of the bank connected to the airspeed static pressure. A simple vertical accelerometer and pendulum inclinometer should be installed on the board and, in addition, should be shown in the photo. Various means have been successfully used for transcribing such manometer data, the simplest of which appears to be a ground-glass screen ruled with a graduated scale completely across the face and used in a projection viewer in conjunction with gage-point markings on the manometer board for adjusting the enlargement to the correct scale. The ruled ground glass can then be shifted to index with the two static manometers, which permits all the other manometers to be read directly from the scale. No data should be transcribed if appreciable acceleration is indicated or if the inclinometers are not square with the indexed scale. Suitable low-temperature fluid should be used. Water traps should be avoided and all pressure lines should be checked for their existence at frequent intervals as well as for leaks and proper connections in the lines.

B. Temperatures

Except for exhaust gas, all temperatures should be measured with either iron constantan, copper constantan, or copper copnic thermocouples or small resistance bulb elements. Quick recording type instruments are available, which are satisfactory for flight service, that will work with either temperature sensitive element. Such a recorder can be employed to take all temperatures by the proper grouping of the sequence of observations so that the performance data temperatures are observed at approximately the same time the photo readings are made.

1. In fighter-type aircraft there is seldom room to install such recorders in addition to a photo panel. In this case direct indicating instruments for temperature are required on the photo panel and all performance data temperatures may be taken by resistance bulbs in conjunction with ratio-type indicating meters. Most flight type of indicating thermocouple meters are unsatisfactory on accuracy and stability counts for this use.

2. Exhaust-gas temperatures and metal associated therewith should be taken by using chromel-alumel thermocouples used with the appropriate instruments. Since most of these temperatures are informative data they may be manually observed with an indicating- or potentiometer-type instrument, but the nozzle-box inlet temperature should be indicated on a cold junction compensated millivoltmeter on the photo panel and employ a shielded type of thermocouple in the exhaust pipe. (See p. 34 for reference 1.) The shielded couple is essential to reduce the error due to radiation to the much colder pipe, an error which may amount to 200° F in some installations.

3. It is highly desirable to take differential temperature readings on the compressor rise and the

intercooler drops. This may readily be accomplished by using iron-constantan thermocouples or their equivalent arranged in series with all the cold junctions on one side and the hot junctions on the other side of the heat exchanger, turbo, and so forth. Copper leads should be used from the harness and the junctions between copper and thermocouple wire must be made in the same duct and located together as they form the equivalent of one junction. The output from the copper leads is connected to a standard millivoltmeter on the photo panel. This system has the advantages of multiplying the voltage available thus allowing the use of a rugged meter without losing accuracy or sensitivity, eliminating the cold-junction compensating errors, and providing an averaging means for sensing the temperature in various places in the duct. It is not essential to use special instrument dials graduated in temperature as the over-all calibration curve can be used instead of the usual calibration correction curve. At least five pairs of couples should be used for compressor rise and engine air drop in the intercooler. For measuring the cooling air rise throughout the intercooler the number of couples required depend on the ducting setup. In the usual case, where the cooling air discharges into a plenum chamber, a minimum of 12 to 16 pairs of couples should be used and spaced symmetrically with respect to the intercooler face so that each couple is located in the middle of an equal flow area. The couple wire may be threaded through the air channels and joined about an inch or so away from the face.

C. Rates and Position Indicators

Those items can employ standard flight instruments which have been carefully inspected and checked for calibration and stability.

1. Time - Standard aircraft clock with a second hand.

2. Engine and turbine revolutions per minute may be indicated with direct-cable connected instruments or remote indicating electric-type instruments.

3. Fuel flow may be indicated by one of several types of meter. None of the commercial articles have reached the point of reliability and accuracy which is desired yet they still contribute a valuable indication affecting engine functions. A direct reading meter on the photo panel is essential for this instrument.

4. Indicated airspeed may be taken by the usual airplane instrument. Only on airplane performance tests is exact airspeed required.

5. Carburetor air flow should preferably be measured by the use of venturi meters in the duct between intercoolers and carburetor. An airspeed head may be used for the pressure differential reading. This meter should be calibrated against standard orifice meters in association with the intercoolers, ducts, and carburetor scoop assembled as used in the flight installation.

6. Carburetor-throttle position, waste-gate position, mixture-control setting, and various other required position indications can be handled by either direct mechanical linkage (where feasible) to the photo panel, or by the use of Selsyn or Autosyn remote indicating equipment.

VIII. PRESENTATION OF RESULTS

A. Tabulation and Plotting of Test Data

The reduction of test data must be designed to permit speed, accuracy, and usefulness of the test data. It is essential that data be available and ready for analysis as soon as possible after a flight, and preferably before the next flight of the program. These requirements demand that transcription of the data be accomplished immediately after landing. In order to be organized in useful form, the performance data must be segregated from the installation data and tabulated (corrected for instrument error) in logical order on a performance data sheet.

1. Plotting of Performance Data

   a. For climb, plot the following against pressure altitude. (See fig. 15.)

      Engine brake horsepower

      Turbo speed

      Waste-gate position

      Indicated airspeed

      Manifold pressure

      Compressor discharge pressure

      Carburetor pressure

      Nozzle-box pressure

      Compressor inlet pressure

      Standard atmospheric pressure (reference 2)

      Exhaust gas temperature at nozzle box

      Compressor discharge temperature

      Carburetor temperature

      Compressor inlet temperature

      Outside air temperature

      Standard atmospheric temperature (reference 2)

   b. For a series of level flights at various engine powers, it has been found very useful to plot the basic data listed above against turbine revolutions per minute for a given altitude. Examples are shown in figures 11, 12, 13, and 14.

   c. Correct all curves in a and b above for deviation of outside air temperature from NACA standard temperature and replot.

2. General Operating Conditions of Installation

   a. Cooling: (Engine, turbosuperchargers, exhaust shrouding, magnetos, generator, etc.). Plot all available data against pressure altitude for constant engine power, indicated airspeed, cowl-flap position and flight condition (climb and level flight).

   b. Lubrication: (Engine and turbosupercharger oil systems). Plot data against pressure altitude and time for rated power climb and normal descent from altitude. Plot against time for military, rated, and cruising power in level flight at maximum altitude.

3. Ground Tests

   a. Plot variables as listed in 1 above against manifold pressure each for constant engine revolutions per minute.

4. Flight

   a. On installation tests the data should be plotted as in 2 and 3 above.

   b. On performance tests the data should be plotted as in 1 above.

5. Special Tests

   a. Special tests will be plotted according to agreement between interested parties.

B. Presentation and Analysis of Results

1. Curves plotted in A. above are presented as results as well as serving as a source of data for calculations and for cross-plots are shown in figure 15.

2. Correlation of flight-test results with those arrived at in preflight analysis: The data obtained in level flight should be reduced to the conditions assumed in the preflight analysis and plotted on the combined performance charts (fig. 10). The degree of correlation and consistency

3. Various plots of one significant variable against another may be used to provide data from which to plot special curves on the basic air flow and carburetor pressure coordinates. For example, plot waste-gate position against engine speed at constant turbosupercharger speed so that waste-gate-position lines may be plotted on the basic engine-turbosupercharger curves. Plots of installation data to prove safe and normal functioning of the installation should be constructed to suit the particular conditions involved.

In general, the final analysis will follow the form of the preflight analysis. The practice will insure rapid interpretation of the results and the analysis of the data.

REFERENCES

1. King, W. J.: Measurement of High Temperatures in High-Velocity Gas Streams. A.S.M.E. Trans., vol. 65, no. 5, July 1943, pp. 421-431.

2. Diehl, Walter S.: Standard Atmosphere - Tables and Data. NACA Rep. No. 218, 1925. Reprint 1940.

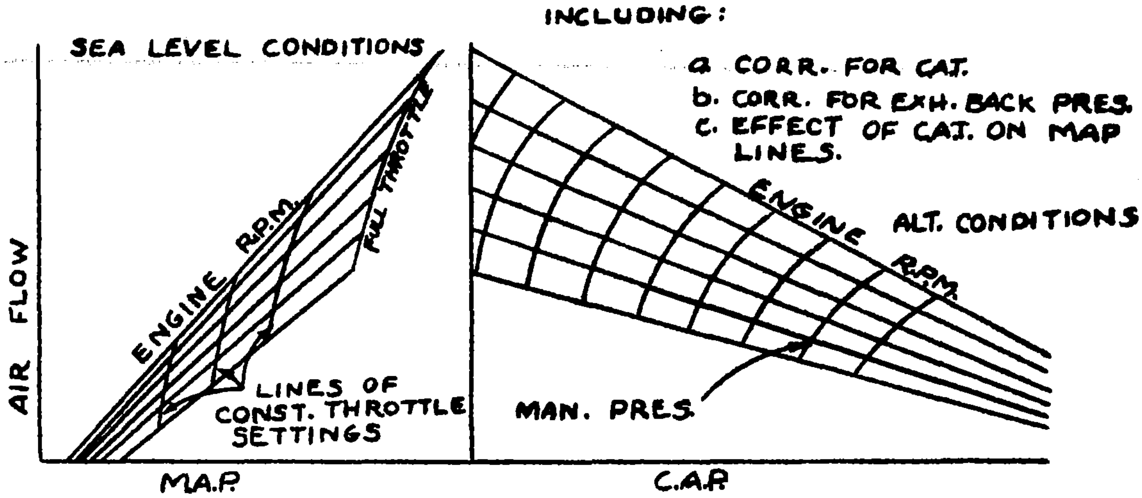


FIG. 1

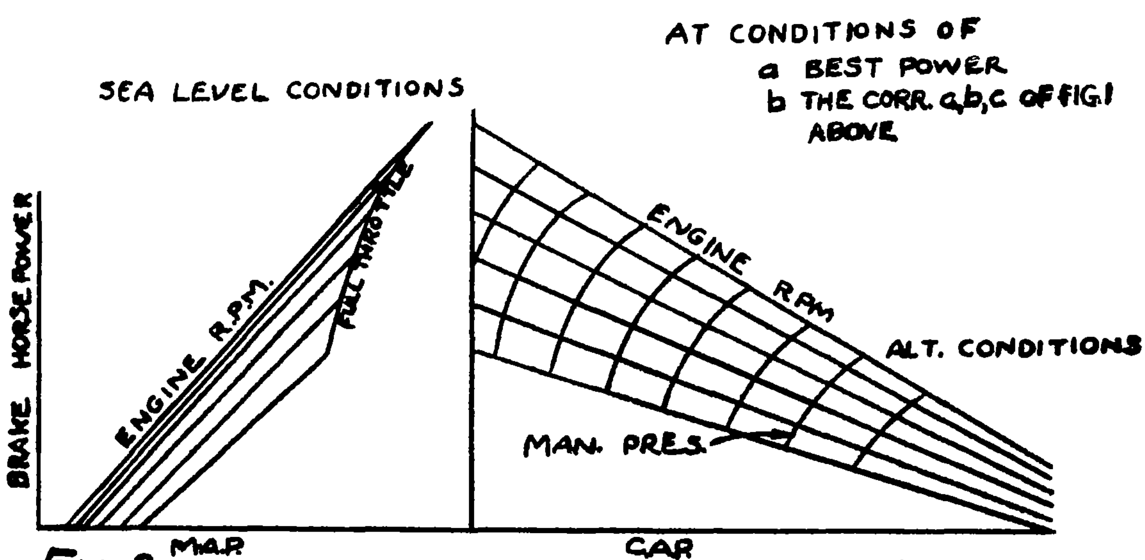


FIG. 2 Data required from the engine manufacturers for pre-flight analysis of turbo supercharged aircraft power plant.

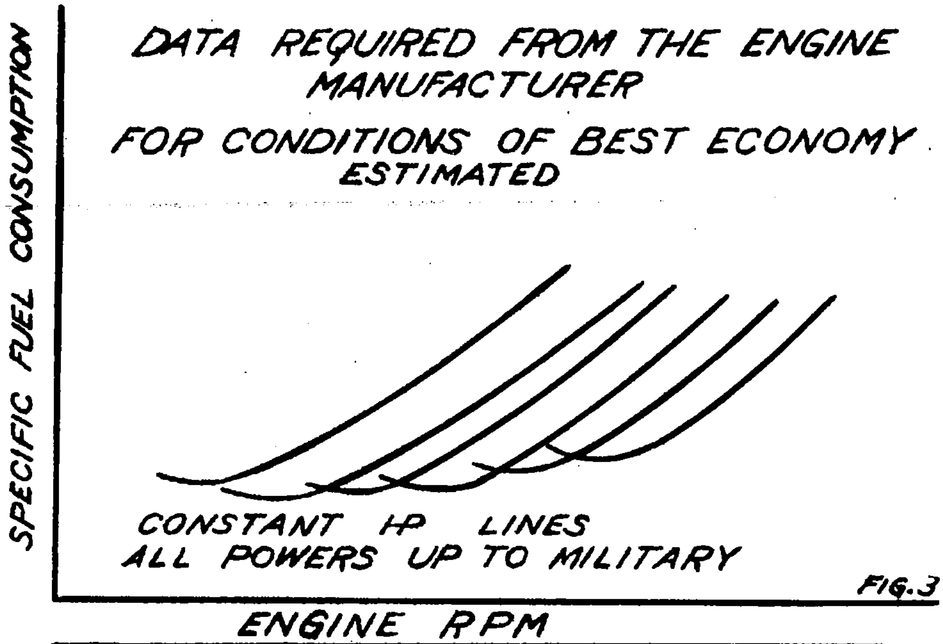

DATA REQUIRED FROM THE ENGINE MANUFACTURER
FOR CONDITIONS OF BEST ECONOMY
ESTIMATED
SPECIFIC FUEL CONSUMPTION
CONSTANT HP LINES
ALL POWERS UP TO MILITARY
ENGINE RPM

FIG. 3

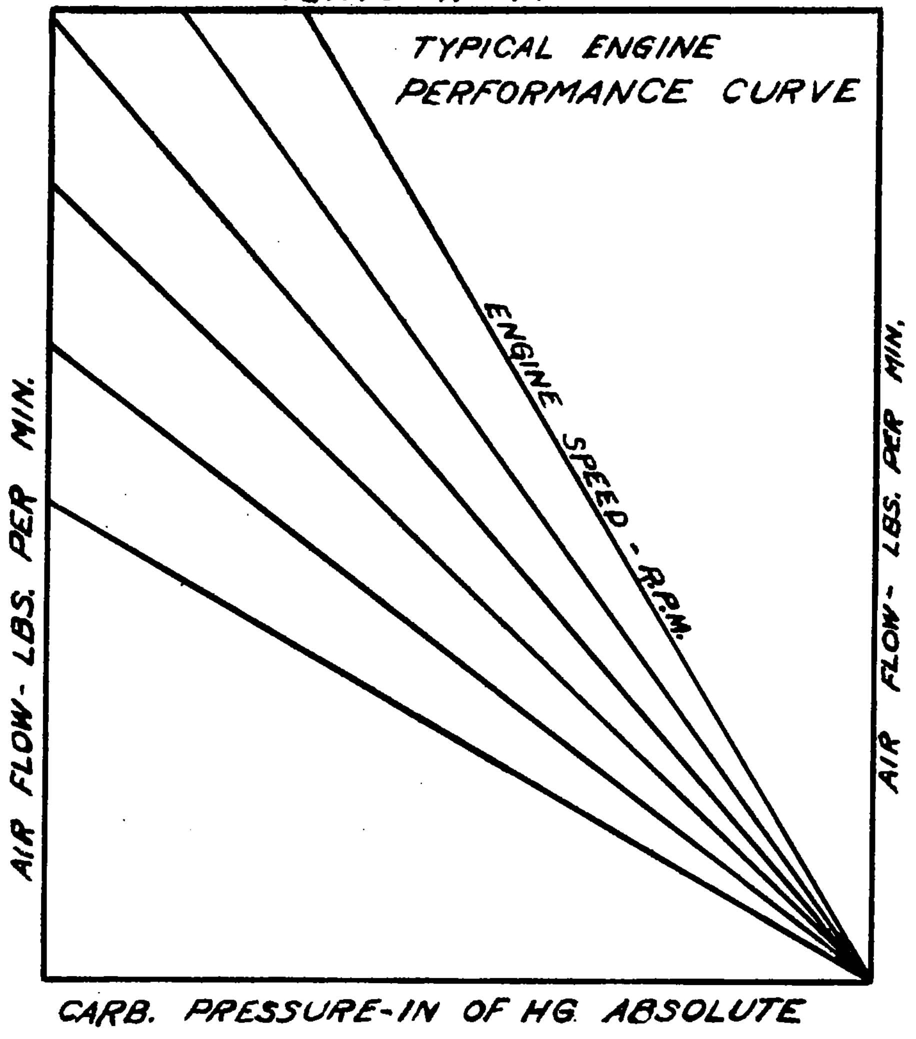

TYPICAL ENGINE PERFORMANCE CURVE
ENGINE SPEED - R.P.M.
AIR FLOW - LBS. PER MIN.
AIR FLOW - LBS. PER MIN.
CARB. PRESSURE-IN OF HG ABSOLUTE

FIG. 4

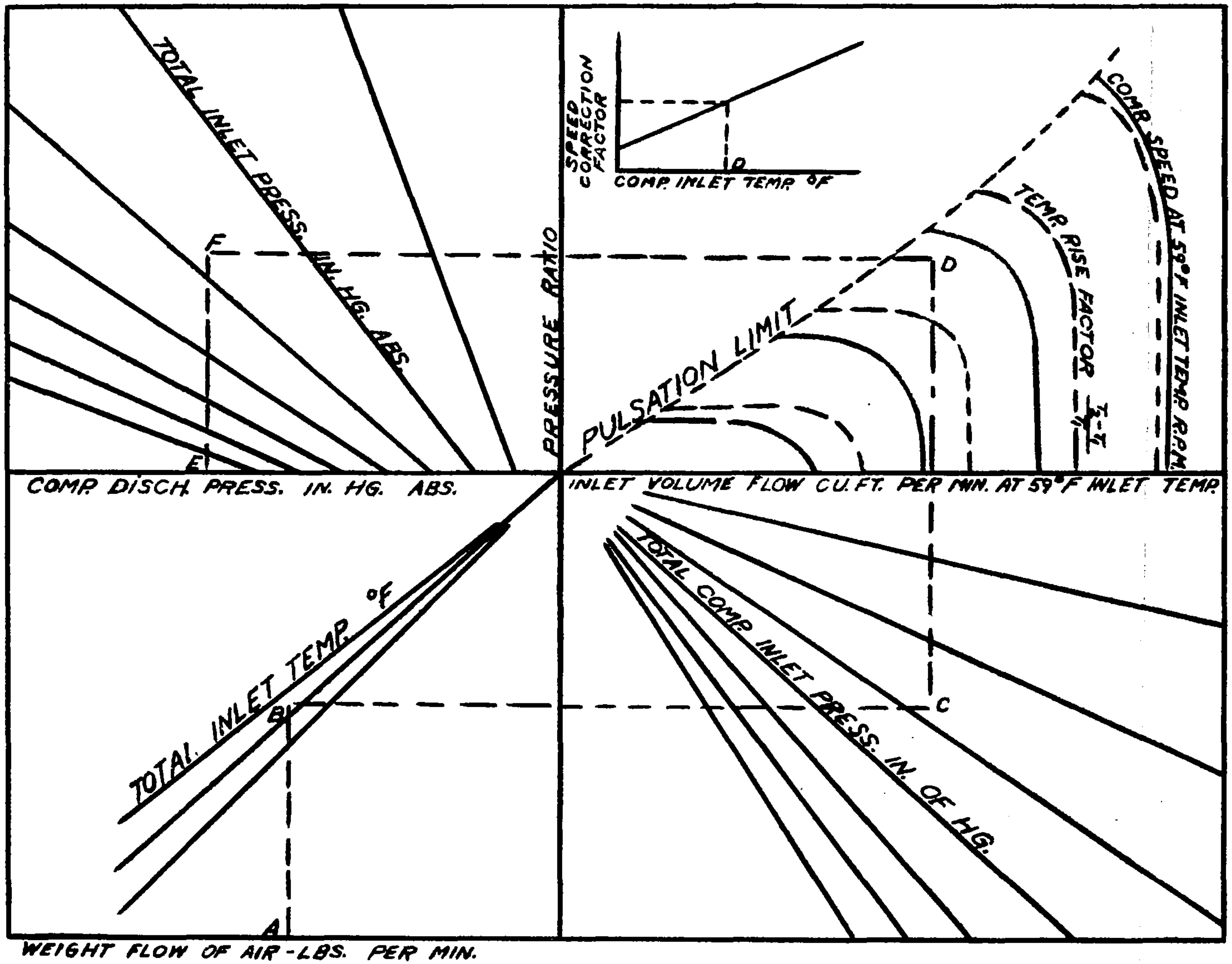


FIG. 5.- Compressor performance data required from the Turbo manufacturer.

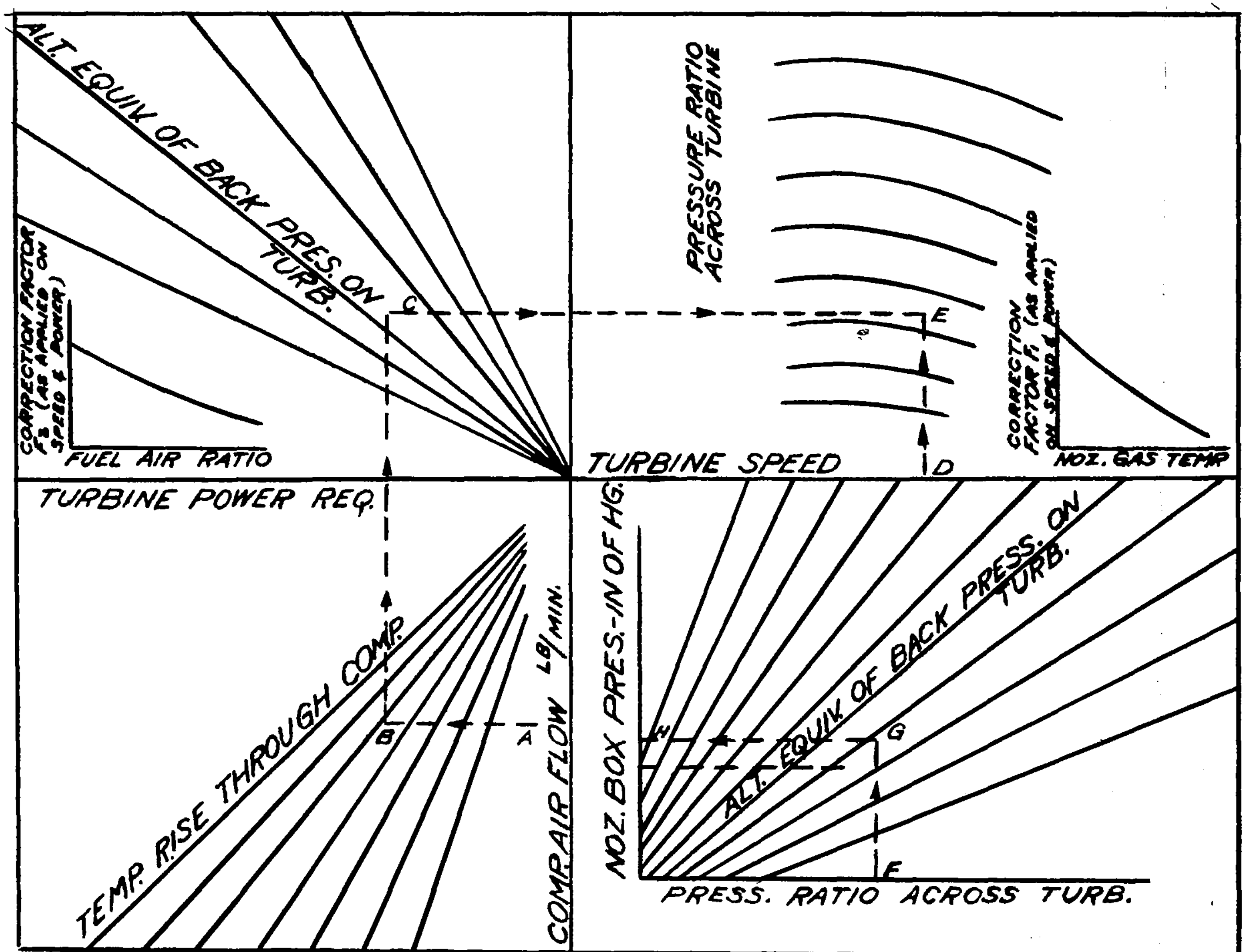
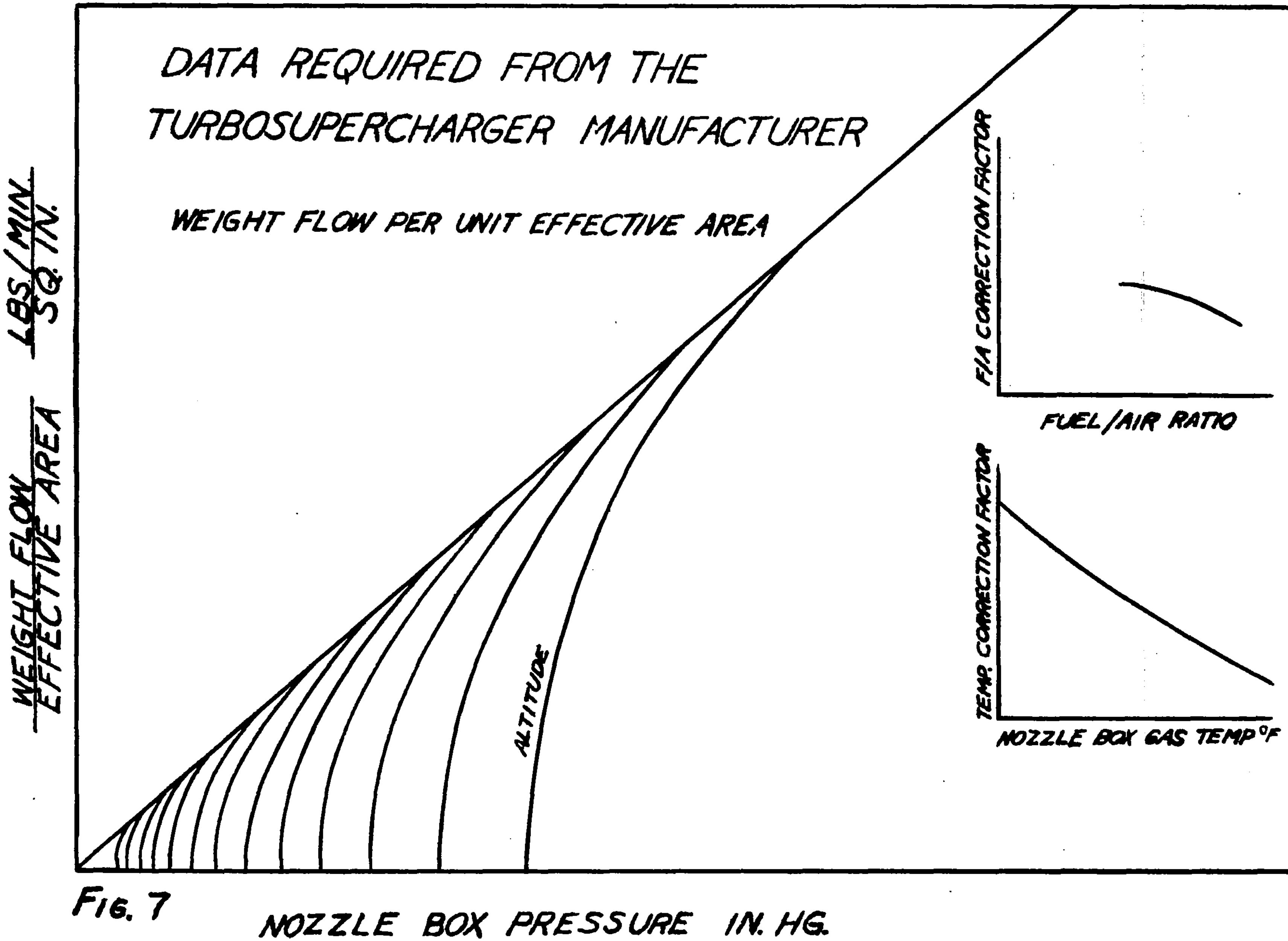


FIG. 6.- Turbine performance data required from the supercharger manufacturer.



DATA REQUIRED FROM THE TURBOSUPERCHARGER MANUFACTURER
WEIGHT FLOW PER UNIT EFFECTIVE AREA
WEIGHT FLOW / EFFECTIVE AREA
LBS/MIN / SQ.IN.
ALTITUDE
NOZZLE BOX PRESSURE IN. HG.
F/A CORRECTION FACTOR
FUEL/AIR RATIO
TEMP. CORRECTION FACTOR
NOZZLE BOX GAS TEMP °F
NACA

FIG. 7

Fig. 7

DATA REQUIRED FROM THE TURBOSUPERCHARGER MANUFACTURER

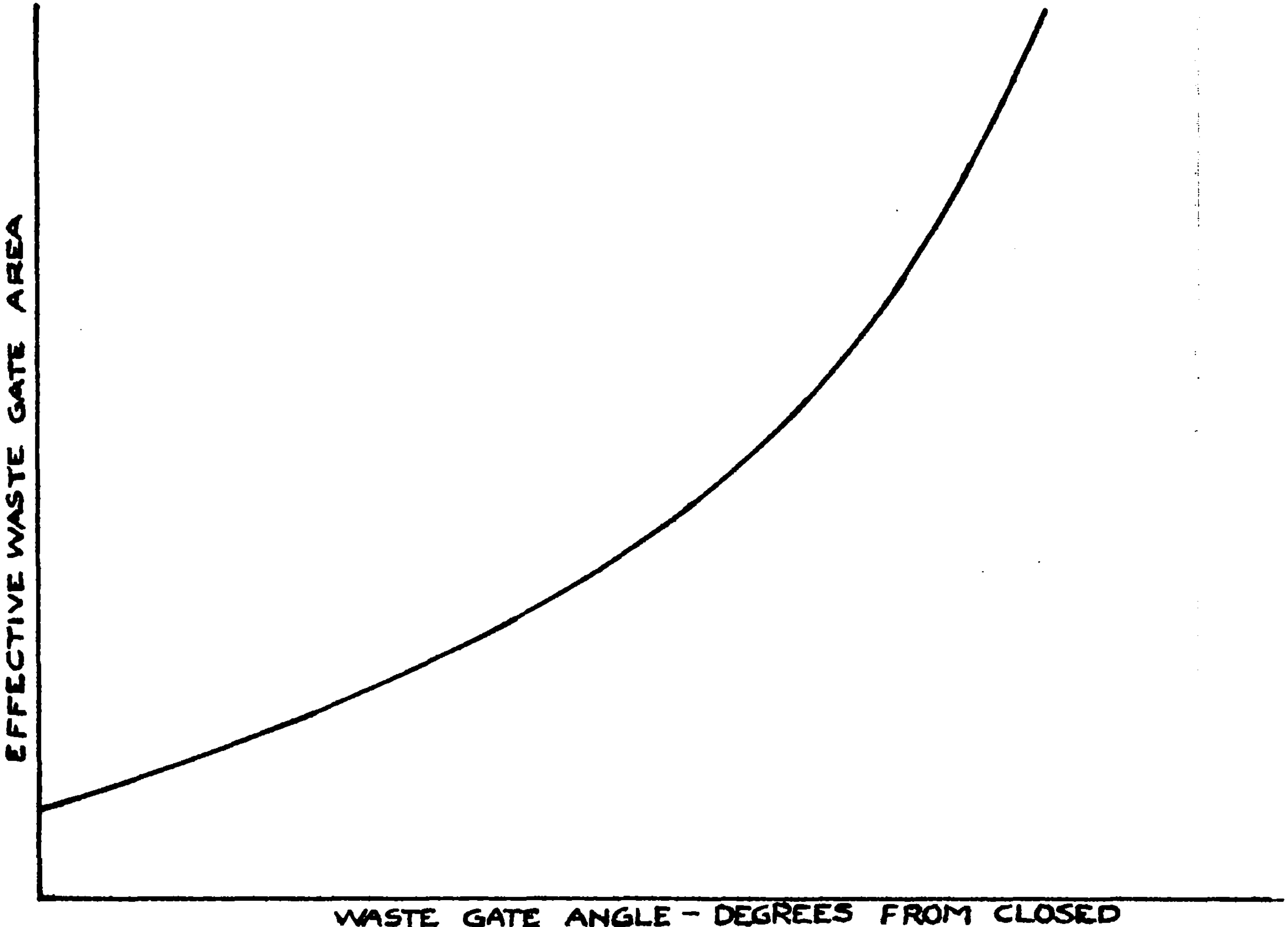


FIG. 8

NACA

NORMAL VARIATION AT STABILIZED CONDITIONS

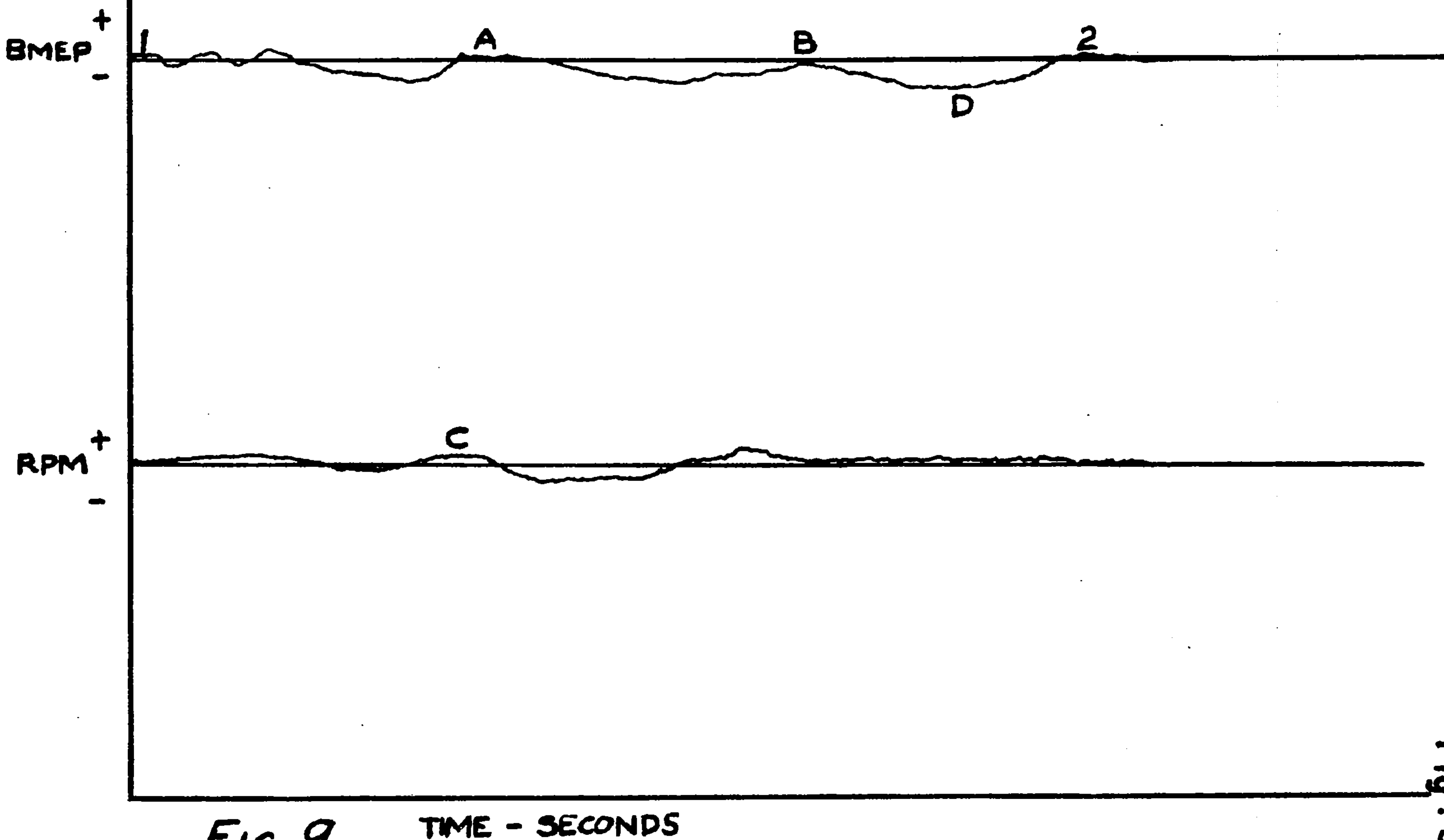


FIG. 9

Fig. 9

NACA TYPICAL ENGINE-TURBOSUPERCHARGER COMBINED PERFORMANCE CHART Fig. 10

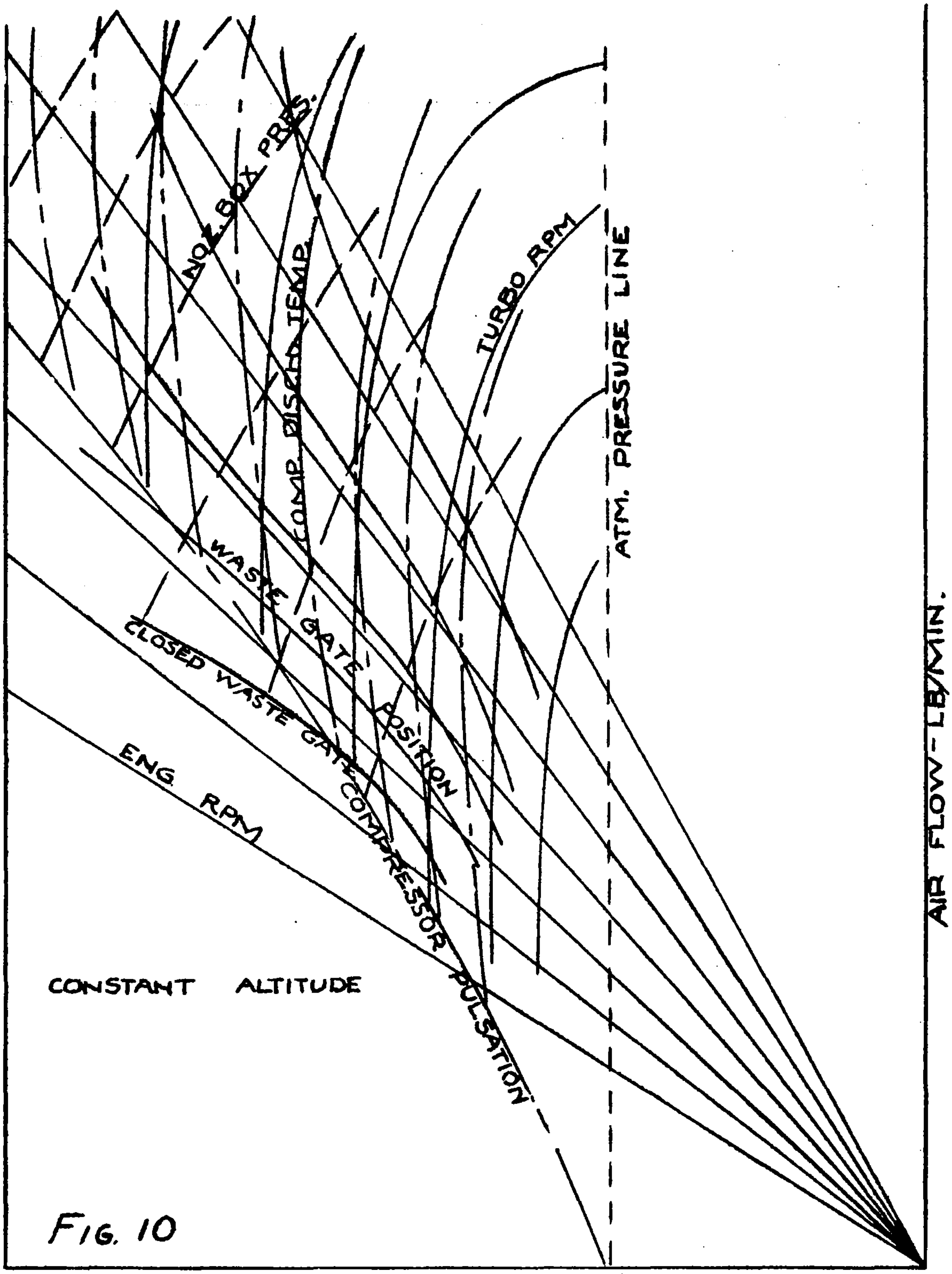


FIG. 10

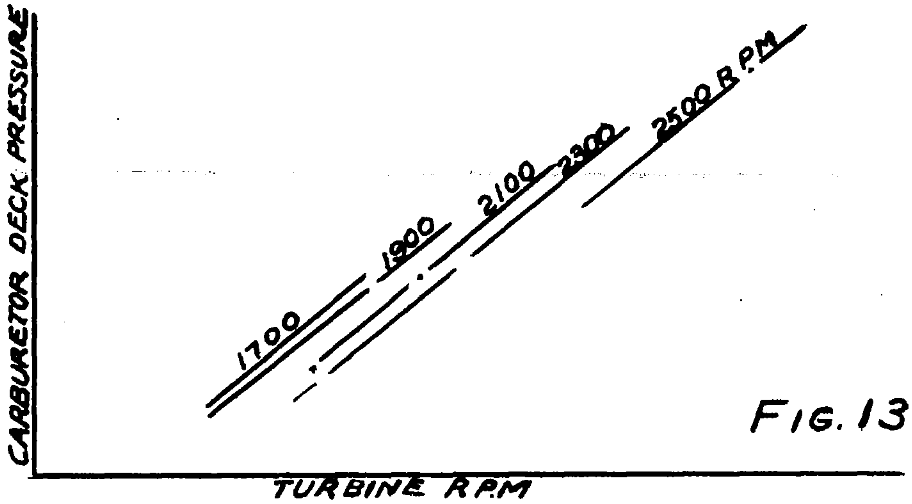


FIG. 13

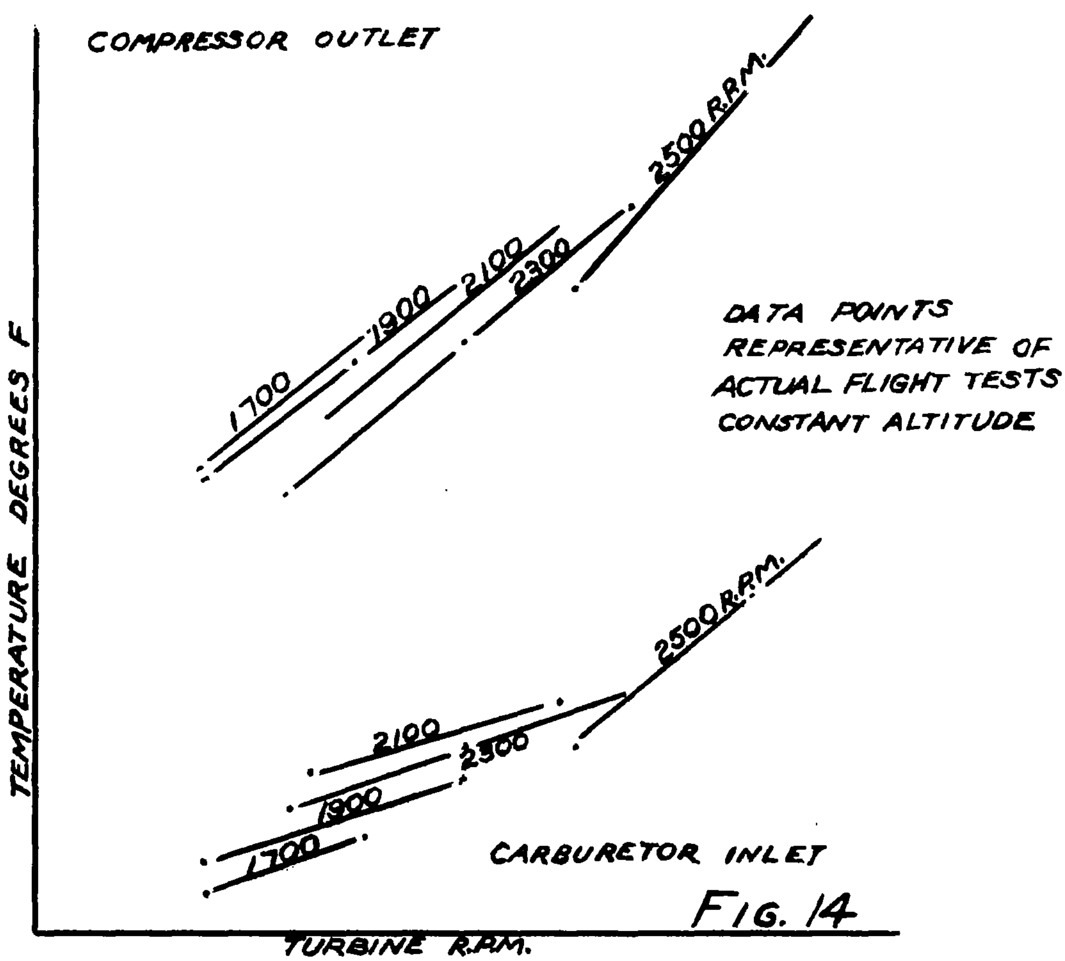


FIG. 14

TYPICAL BASIC DATA PRESENTATION

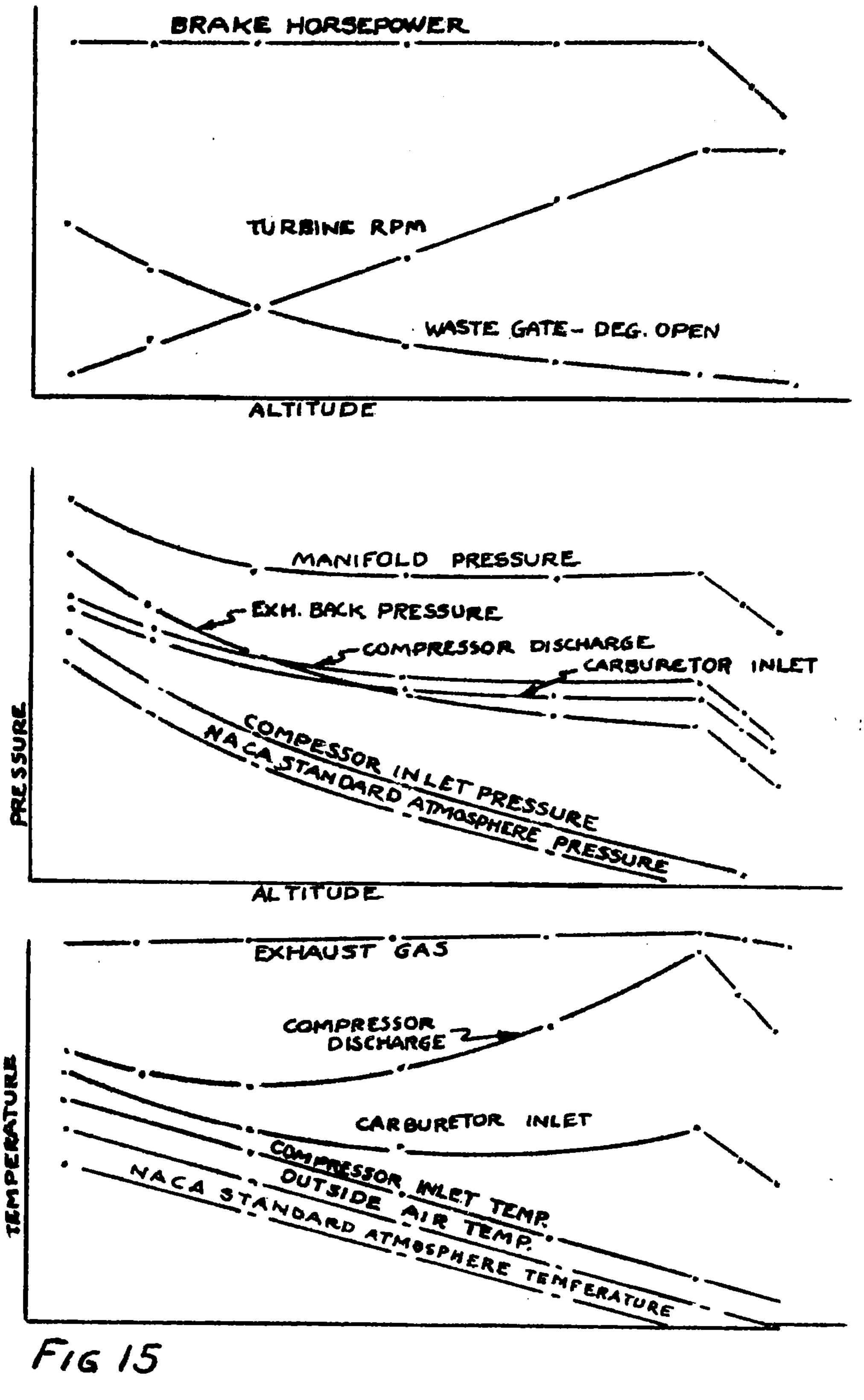

BRAKE HORSEPOWER
TURBINE RPM
WASTE GATE - DEG. OPEN
ALTITUDE
MANIFOLD PRESSURE
EXH. BACK PRESSURE
COMPRESSOR DISCHARGE
CARBURETOR INLET
COMPRESSOR INLET PRESSURE
NACA STANDARD ATMOSPHERE PRESSURE
PRESSURE
ALTITUDE
EXHAUST GAS
COMPRESSOR DISCHARGE
CARBURETOR INLET
COMPRESSOR INLET TEMP.
OUTSIDE AIR TEMP.
NACA STANDARD ATMOSPHERE TEMPERATURE
TEMPERATURE

FIG 15